A METHOD OF COMPENSATING FOR CORRELATION BETWEEN MULTIPLE ANTENNAS

CROSS-REFERENCE TO RELATED APPLICATION

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FIELD OF THE INVENTION

The present invention relates to telecommunications, and more particularly, wireless communication.

DESCRIPTION OF THE RELATED ART

Base station antennas are often placed high above ground and relatively close to each other. There may be no obstructions between them acting to scatter transmitted symbols, leading to high antenna correlation. It has been shown that such correlations reduce channel capacity and system performance in multiple-input multiple-output ("MIMO") systems.

Specifically, performance degradation due to antenna correlation may be prevented by increasing the spacing of antennas. However, it has been found that in situations where the angular spread of radio waves reaching an antenna is relatively small or where there are no line of sight obstructions between antennas, antenna correlation may be high (e.g., taking a value close to one) even when the antennas are well-separated.

Accordingly, those skilled in the art have recognised that antenna correlations tend to degrade the performance of MIMO systems.

SUMMARY OF THE INVENTION

The present invention provides for a method of linear transformation for a space-time coded system, which may alter transmitted signals to at least partially compensate for antenna correlation. The linear transformation may be realized by a precoder, for example, which combats the detrimental effects of antenna correlation by exploiting knowledge of antenna correlation made available to the transmitter.

In one example of the present invention, a method is provided for transmitting signals from two or more antennas in a wireless telecommunications network, in which at least one data sequence may be space-time block encoded. Before transmitting the data sequence, a linear transformation may be applied to the data sequence, the linear transformation being dependent upon knowledge of correlation among the antennas to at least partially compensate the transmitted signals for said correlation. The linear transformation may depend on the eigenvalues of an antenna correlation matrix. The linear transformation may also depend on a ratio of symbol energy (E_s) to noise variance (σ^2). The method may includes transmitting the encoded and transformed data sequence.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be better understood from reading the following description of non-limiting embodiments, with reference to the attached drawings, wherein below:

Figure 1 is a diagram illustrating a MIMO telecommunications system;

Figure 2 is a diagram illustrating a UMTS transmitter and receiver;

Figure 3 is a diagram illustrating an alternative UMTS transmitter and receiver;

Figure 4 is a diagram illustrating a further UMTS transmitter and

receiver; and

Figure 5 is a diagram illustrating a yet further UMTS transmitter and receiver.

It should be emphasized that the drawings of the instant application are not to scale but are merely schematic representations, and thus are not intended to portray the specific dimensions of the invention, which may be determined by skilled artisans through examination of the disclosure herein.

DETAILED DESCRIPTION

For ease of understanding a more general description is presented, followed by an explanation of implementation aspects in a mobile telecommunications network, such as a Universal Mobile Telecommunications System ("UMTS") standards based type. It should be noted that the present invention has applications not only in UMTS, but also, by way of example and without limitation, in communication systems such as, for example, code division multiple access ("CDMA") and wideband code division multiple access ("W-CDMA").

MIMO systems for use in UMTS, for example, typically involve space-time block encoding. The encoding and transmission sequence for this scheme may be as follows: at a first transmission time instant t_1 symbols x_1 and x_2 may be transmitted from antennas 1 and 2 respectively and at the next transmission instant t_2 symbols $-x_2^*$ and x_1^* may be transmitted from antennas 1 and 2 respectively, where * denotes complex conjugate. This transmission sequence **Z** can be represented in matrix form as $\begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix}$.

In the case of four antennas in the above space-time block encoding scheme, the transmission sequence **Z** may be represented in matrix form as

$$\mathbf{Z} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & -x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{bmatrix}$$

It should be noted that the performance of MIMO systems can sometimes be improved by precoding. Precoding may be defined to means applying a linear transformation to symbols. This precoder may be a function of both the matrices of eigenvectors and eigenvalues of the antenna correlation matrix **R**. Specifically, the optimal precoder **L**, which may be optimal in the sense that the average Pairwise Error Probability ("PEP") between two codewords is minimized, may beproved as follows:

$$\mathbf{L} = \mathbf{V}_r \mathbf{\Phi}_r \mathbf{V}_e^H \qquad \text{(Equation 1)}$$

where $\mathbf{R}^{1/2} = \mathbf{U}_r \mathbf{\Lambda}_r \mathbf{V}_r$, with $\mathbf{U}_r$ and $\mathbf{V}_r$ being the matrices of eigenvectors of the matrix $\mathbf{R}^{1/2}$ and Λ_r being the matrix of eigenvalues of $\mathbf{R}^{1/2}$. **R** is the antenna correlation matrix. $\mathbf{\Phi}_r^2 = (\gamma \mathbf{I} - \mathbf{\Lambda}_r^{-2}\mathbf{\Lambda}_e^{-2})_+$, with **I** being the identity matrix, and $\mathbf{EE}^H = \mathbf{U}_e \mathbf{\Lambda}_e \mathbf{V}_e$, **E** being the matrix of the minimum distance of the code, with $\mathbf{U}_e$ and $\mathbf{V}_e$ being the matrices of eigenvectors of $\mathbf{EE}^H$ and Λ_e being the matrix of eigenvalues of $\mathbf{EE}^H$. $\gamma > 0$ is a constant that is computed from the

transmit power and $(\cdot)_+$ denotes that the expression in the parenthesis takes its actual computed value if positive else is set to zero if negative.

A linear precoder that exploits knowledge of antenna correlation may be included in a space-time coded MIMO system so as to enhance performance. Let us consider a multiple-input multiple output ("MIMO") telecommunications network consisting of M transmit antennas and N receive antennas, as shown in Figure 1. The transmitter, for example a base station for mobile telecommunications, has some knowledge about the channel, namely the antenna correlation matrix **R**. There is a channel matrix **H,** which describes the physical characteristics of the propagation channel. More specifically, each entry h_{ji} of the NxM channel matrix **H** represents the channel response between transmit antenna i and receive antenna j. The space-time encoder of the transmitter maps the input data sequence $x=(x_1,x_2,..x_Q)$ to be transmitted into an MxQ matrix Z of codewords, that are split on a set of M parallel sequences. I.e. , each of the M rows of the matrix **Z** represents one of Q distinct codewords. These codewords are then transformed by a MxM linear transformation denoted **L** in order to adapt the code to the available antenna correlation information. The resulting sequences, which are represented by rows of a new transformed MxQ matrix **C=LZ,** are sent from the M transmit antennas over Q time intervals.

The receive signal (at the mobile) is assumed to be a linear combination of several multipaths reflected from local scatterers, which result in uncorrelated fading across the receive antennas and therefore uncorrelated rows of matrix **H**. However, limited scattering at the transmitter (e.g. a base station), can result in antenna correlation and hence correlated columns of channel matrix **H**. A correlation among the M transmit antennas may be described by the MxM matrix **R,** referred to as the (transmit) antenna correlation matrix. The signal received by the N receive antennas over Q time periods may be represented by an NxQ matrix **Y.** The received signal

included in the matrix **Y** may then be a superposition of M transmitted sequences corrupted by an additive white Gaussian noise characterised by the NxQ matrix **Σ** and with covariance matrix equal to $\sigma^2 I_N$:

$$\mathbf{Y} = \mathbf{HC} + \mathbf{\Sigma} = \mathbf{HLZ} + \mathbf{\Sigma} \qquad \text{(Equation 2)}$$

The linear transformation **L** may be determined so as to minimise a given criterion, namely an upper bound on the pairwise error probability (PEP) of a codeword. The determination of **L**, as described here, assumes for mathematical simplification that the transmitter possesses perfect knowledge of the antenna correlation matrix. This precoder **L** is a function of both the matrices of eigenvectors and eigenvalues of the antenna correlation matrix. Specifically, the optimal precoder **L**, which minimizes the average PEP is:

$$\mathbf{L} = \mathbf{V}_r \mathbf{\Phi}_f \mathbf{V}_e^H \qquad \text{(Equation 3)}$$

where $\mathbf{R}^{1/2} = \mathbf{U}_r \mathbf{\Lambda}_r \mathbf{V}_r$, with U_r and V_r being the matrices of eigenvectors of the correlation matrix $R^{1/2}$ and Λ_r being the matrix of eigenvalues of $\mathbf{R}^{1/2}$. **R** is the antenna correlation matrix. $\mathbf{\Phi}_f^2 = \left(\gamma \mathbf{I} - \left(\frac{E_s}{\sigma^2} \right)^{-1} \mathbf{\Lambda}_r^{-2} \mathbf{\Lambda}_e^{-2} \right)_+$, with **I** being the identity matrix and $\mathbf{EE}^H = \mathbf{U}_e \mathbf{\Lambda}_e \mathbf{V}_e$, where $\mathbf{E} = \arg \min_{\tilde{\mathbf{E}}(k,l,t)} \det\left[\tilde{\mathbf{E}}(k,l,t)\tilde{\mathbf{E}}^H(k,l,t)\right]$ is the matrix of the minimum distance of the code, with U_e and V_e being the matrices of eigenvectors of $\mathbf{EE}^H$ and Λ_e the matrix of eigenvalues of $\mathbf{EE}^H$. Also, $\gamma > 0$ is a constant that is computed from the transmit power P_O and $(\cdot)_+$ denotes that the expression in the parenthesis takes its actual computed values if positive else is set to zero if negative. It will be seen that there is an

additional term $\left(\frac{E_s}{\sigma^2}\right)^{-1}$, where E_s is the symbol energy and σ^2 is the noise variance. This term was included so as to account for Signal-to-Noise Ratio, which is E_s/σ^2.

Since an orthogonal space-time code is considered, $\mathbf{E}\mathbf{E}^H = \zeta\mathbf{I}$, where ζ is a scalar, $\mathbf{\Lambda}_e = \zeta\mathbf{I}$ and $\mathbf{V}_e = \mathbf{I}$. This gives rise to the following equation:

$\mathbf{L} = \mathbf{V}_r\mathbf{\Phi}_f$ (Equation 4).

Application to an M antenna transmission system

Considering the general case of m transmit antennas, the next step may be to apply both the linear precoder **L** given in Equation (4) and any orthogonal space-time block coding **Z** to Equation (2). $\mathbf{\Lambda}_e = \mathbf{I}$ and $\mathbf{V}_e = \mathbf{I}$. $\mathbf{V}_r$ and $\mathbf{\Phi}_f^2$ coincide with the matrix with the eigenvectors and eigenvalues of $\mathbf{L}\mathbf{L}^H$ respectively. Without loss of generality we assume that the transmit power Po, equal to the trace of $\mathbf{L}\mathbf{L}^H$, may be 1. With $\lambda_{r,1}, \lambda_{r,2}, \ldots, \lambda_{r,M}$ being the eigenvalues of matrix $\mathbf{R}^{1/2}$ where $\lambda_{r,1} \geq \lambda_{r,2} \geq \ldots \geq \lambda_{r,M}$ and $\mathbf{w}_1, \mathbf{w}_2, \ldots, \mathbf{w}_M$ being the corresponding eigenvectors of the matrix $\mathbf{R}_T^{1/2}$, the linear precoder is characterised as follows:

1) When the antenna correlation is less than one, $\lambda_{r,1}, \lambda_{r,2}, \ldots, \lambda_{r,M} \neq 0$ and $\beta_i = \left[\left(\frac{1}{\lambda_{r,1}^2} - \frac{1}{\lambda_{r,i}^2}\right) + \left(\frac{1}{\lambda_{r,2}^2} - \frac{1}{\lambda_{r,i}^2}\right) + \cdots + \left(\frac{1}{\lambda_{r,M}^2} - \frac{1}{\lambda_{r,i}^2}\right)\right] \Big/ \left(\frac{\mathbf{E_S}}{\boldsymbol{\sigma}^2}\right) \geq -1, i = 1,2,\ldots,M$, the precoder matrix may be:

$$\mathbf{L}=\frac{1}{\sqrt{\mathrm{M}}}\begin{bmatrix}\mathbf{w}_1 & \mathbf{w}_2 & \cdots & \mathbf{w}_\mathrm{M}\end{bmatrix}\begin{bmatrix}\sqrt{1+\beta_1} & 0 & 0 & \cdots & 0\\ 0 & \sqrt{1+\beta_2} & 0 & \cdots & 0\\ 0 & 0 & \ddots & 0 & \vdots\\ \vdots & \vdots & 0 & \ddots & 0\\ 0 & 0 & \cdots & 0 & \sqrt{1+\beta_\mathrm{M}}\end{bmatrix}$$

(Equation5)

2) When the antenna correlation is zero, the eigenvalues of the matrix $\mathbf{R}^{1/2}$ are equal and therefore $\beta_i=0$, for $i=1,2,\ldots,\mathrm{M}$. Also, the matrix of the eigenvectors equals the identity matrix. In this case the precoder may be equivalent to the orthogonal space-time coding.

3) When the antenna correlation is one, only one eigenvalue of matrix $\mathbf{R}_T^{1/2}$ is non zero. In this case the precoder is equivalent to a beamformer.

<u>Application to a Two-antenna transmission system</u>

Looking at the particular case of two transmit antennas, the linear precoder $\mathbf{L}$ of Equation (4) and the matrix of codewords for Alamouti space-time block coding, namely $\mathbf{Z}=\begin{bmatrix}x_1 & x_2\\ -x_2^* & x_1^*\end{bmatrix}$ are applied to Equation (2).

For power $P_o=1$, where $\lambda_{r,1},\lambda_{r,2}$ are the eigenvalues and w_1, w_2 are the eigenvectors of the matrix $\mathbf{R}^{1/2}$, the linear precoder is characterised as follows:

1) When the antenna correlation is less than one, $\lambda_{r,1},\lambda_{r,2}\neq 0$ and $\beta=\left(\frac{1}{\lambda_{r,2}^2}-\frac{1}{\lambda_{r,1}^2}\right)\Big/\left(\frac{\mathbf{E}_\mathrm{S}}{\sigma^2}\right)\leq 1$, the precoder can be written as:

$$\mathbf{L}=\begin{bmatrix}w_1 & w_2^*\\ w_2 & -w_1^*\end{bmatrix}\begin{bmatrix}\sqrt{(1+\beta)/2} & 0\\ 0 & \sqrt{(1-\beta)/2}\end{bmatrix} \qquad \text{(Equation 6)}$$

with $\mathbf{V}_r = \begin{bmatrix} w_1 & w_2^* \\ w_2 & -w_1^* \end{bmatrix}$

and $\mathbf{\Phi}_f = \begin{bmatrix} \sqrt{(1+\beta)/2} & 0 \\ 0 & \sqrt{(1-\beta)/2} \end{bmatrix}$

2) When the antenna correlation is zero, the eigenvalues of the matrix $\mathbf{R}^{1/2}$ are equal and therefore β=0. In this case the precoder becomes $\mathbf{L} = \frac{1}{\sqrt{2}}\begin{bmatrix} w_1 & w_2^* \\ w_2 & -w_1^* \end{bmatrix}$ which is equivalent to the Alamouti orthogonal space-time coding.

3) When the antenna correlation is one, one eigenvalue of matrix $\mathbf{R}^{1/2}$ is zero resulting in a matrix Φ_f with all elements but one equal to zero. In this case the precoder becomes $\mathbf{L} = \begin{bmatrix} w_1 & 0 \\ w_2 & 0 \end{bmatrix}$, which is equivalent to a beamformer.

The proposed reconfigurable scheme may thus be equivalent to orthogonal space-time block coding for antenna correlation equal to zero, and to beamforming for antenna correlation equal to one. For intermediate antenna correlation values it performs well and may be robust to antenna correlation variations.

The decoder in a two-antenna transmission system

The space-time decoder at the receiver is similar to the one used with Space-Time Block Codes, except that the linear transformation matrix **L** may be taken into account. The received signal described in Equation (2) can be seen as $\mathbf{Y} = \lfloor y_1 \quad y_2 \rfloor = \mathbf{H}_{eq}\mathbf{Z} + \mathbf{\Sigma} = \mathbf{HLZ} + \mathbf{\Sigma}$, where $\mathbf{H}_{eq} = \lfloor h_{eq,1} \quad h_{eq,2} \rfloor = \mathbf{HL}$. The space-time block decoder for the proposed approach can then be seen as identical with the conventional one under the assumption that the effective channel is now $\mathbf{H}_{eq}$. Hence, to recover the transmitted signals x_1 and x_2, the following operations are realized:

$$\hat{x}_1 = \left(h_{eq,1}\right)^* y_1 - h_{eq,2}\left(y_2\right)^*$$
$$\hat{x}_2 = \left(h_{eq,2}\right)^* y_1 + h_{eq,1}\left(y_2\right)^*$$

It will be seen that knowledge of the equivalent channel $\mathbf{H}_{eq}$ (or its estimate) may be required at the receiver in order to recover the transmitted signals x_1 and x_2.

Two-antenna transmission system implementation in UMTS

A UMTS transmitter 2 and receiver 4 are shown in Figure 2. The UMTS frequency division duplex ("FDD") downlink transmission-reception scheme includes antenna correlation dependent linear precoding as explained above. The transmitter 2 has some knowledge about the channel, namely the antenna correlation matrix **R**. In a UMTS network operating FDD downlink (e.g., from base station to mobile station), the antenna correlation information is obtained as feedback channel estimates 6 provided as bits sent by receiver 4 (e.g., the mobile station). The relevant modules may be, at the transmitter, a linear precoder (**L**) 8, a processor (COR,10) which determines the antenna correlation matrix (**R**), and an R to L converter 12. The relevant modules at the receiver may be a processor (COR,14) which determines the antenna correlation matrix (**R**), an R to L converter 16, and a space-time decoder 18.

At the transmitter 2, the linear precoder (**L**) 8 is applied to the space-time encoded symbols provided from a space-time block encoder 20 after channel coding, rate matching interleaving, and modulation (shown as functional clock 22) in known fashion. The linear precoder L coefficients may be computed based on the antenna correlation matrix **R** in the R to L converter 12. The computation of **R** (in a functional block denoted COR,10) may be based on channel estimates 6 fed back from the receiver 4. It may be performed by averaging over time-sequential channel estimates (running average) using a forgetting factor. The forgetting factor aims to weight the

contribution of each new channel estimate as compared to the past channel estimates. It will thus be seen that fast fading may be not tracked but only slowly varying antenna correlations. This information may be fed back to the transmitter using a low-rate feedback link, as available in UMTS. In a UMTS uplink channel there may be a number of bits available for communicating information to the transmitter about the received signal. The outputs of the linear precoder 8 may be spread/scrambled 9 and subject to addition of Common Pilot Channel (CPICH) coding 11 bits before transmission.

At the receiver 4, received signals may be used to provide channel estimates in a channel estimation block 26 so as to be used to compute the antenna correlation matrix R in processor 14 (as at the transmitter). The signals may be also despread 28 and applied to a space-time block decoder 24. At the receiver 4 the space-time block decoder (STD,24) has essentially the same structure as a conventional one, but needs to consider instead of the channel estimates, the equivalent channel, defined as the linear transformation of the channel according to the coefficients of L, that is $\mathbf{H}_{eq} = \lfloor h_{eq,1} \quad h_{eq,2} \rfloor = \mathbf{HL}$. As shown in Figure 2, the linear precoder **L** coefficients are estimated at the receiver from the processor (COR,14) which determines the antenna correlation matrix (**R**) and the R to L converter 16 present at the receiver 4. The outputs of the space-time decoder 24 may be provided to a combiner 30 and then channel decoded, inverse rate matched, deinterleaved and demodulated in known fashion (shown in Figure 2 as functional block 32).

<u>Alternative Two-antenna Transmission System Implementation in UMTS</u>

An alternative implementation is now described, in which instead of the linear transformation matrix **L** being determined at the transmitter from

channel estimates provided by the receiver, the coefficients of linear transformation matrix L are provided by the receiver.

In this alternative embodiment, which is shown in Figure 3, the transmitter 302 is given the coefficients of the precoder **L** by the receiver 304. In this UMTS transmitter 302 and receiver 304 operating with frequency division duplex (FDD) downlink, these coefficients are feedback bits sent by the mobile station. The proposed UMTS network is depicted in Figure 3, where the UMTS FDD downlink transmission-reception scheme includes antenna correlation dependent linear precoding as explained previously. The relevant module at the transmitter is a linear precoder (**L**) 308. The relevant modules at the receiver are a processor (COR,314) which determines the antenna correlation matrix (**R**), an R to L converter 316, and a space-time decoder 324.

At the transmitter, the linear precoder (**L**) may be applied to the space-time encoded symbols provided from the space-time block encoder 320 after channel coding, rate matching, interleaving, and modulation (shown as functional block 322) in known fashion. The outputs from the linear precoder 308 may be spread/scrambled 309 and subject to the addition of Common Pilot Channel (CPICH) 311 bits before transmission. The linear precoder **L** coefficients may be provided by the receiver 304 as explained below and fed back over air to the transmitter.

At the receiver, the computation of **R** (in a functional block denoted COR 314) may be based on channel estimates provided from the channel estimator block 326. It may be performed by averaging over time sequential channel estimates (running average) using a forgetting factor. The forgetting factor aims to weight the contribution of each new channel estimate as compared to the past channel estimates; the aim being to take account of slowly-varying antenna correlations but not fast fading. The linear precoder

(L) coefficients may be computed based on the antenna correlation matrix **R** in the R to L converter 316.

At the receiver 304, received signals may be both used to provide channel estimates in a channel estimation block 326, and may be also despread 328 and applied to a space-time decoder 324. At the receiver, the space-time block decoder (STD) 324 may have identical structure to the conventional one, but needs to consider instead of the channel estimates, the equivalent channel, defined as the linear transformation of the channel according to the coefficients of L, that is $\mathbf{H}_{eq} = \lfloor h_{eq,1} \quad h_{eq,2} \rfloor = \mathbf{HL}$. The outputs of the space-time decoder may be provided to a combiner 330 and then channel decoded, inverse rate matched, deinterleaved and demodulated in known fashion (shown in Figure 3 as functional block 332).

<u>Application to a Four-antenna transmission system</u>

Turning now to consider the 4 transmit antenna case, the linear precoder given back in Equation (3) and the matrix of codewords for Tarokh space-time block coding for the 4 transmit antenna case, namely

$$\mathbf{Z} = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ -x_2 & x_1 & -x_4 & x_3 \\ -x_3 & x_4 & x_1 & -x_2 \\ -x_4 & -x_3 & x_2 & x_1 \\ x_1^* & x_2^* & x_3^* & x_4^* \\ -x_2^* & x_1^* & -x_4^* & x_3^* \\ -x_3^* & x_4^* & x_1^* & -x_2^* \\ -x_4^* & -x_3^* & x_2^* & x_1^* \end{bmatrix}$$

, are applied to Equation (2).

1) When the antenna correlation may be less than one, $\lambda_{r,1}, \lambda_{r,2}, \lambda_{r,3}, \lambda_{r,4} \neq 0$ and $\beta_i = \geq -1, i = 1,2,3,4$, with

$$\beta_1 = \left[\left(\frac{1}{\lambda_{r,2}^2} - \frac{1}{\lambda_{r,1}^2} \right) + \left(\frac{1}{\lambda_{r,3}^2} - \frac{1}{\lambda_{r,1}^2} \right) + \left(\frac{1}{\lambda_{r,4}^2} - \frac{1}{\lambda_{r,1}^2} \right) \right] \Bigg/ \left(\frac{\mathbf{E_S}}{\boldsymbol{\sigma}^2} \right) \quad (7)$$

$$\beta_2 = \left[\left(\frac{1}{\lambda_{r,1}^2} - \frac{1}{\lambda_{r,2}^2} \right) + \left(\frac{1}{\lambda_{r,3}^2} - \frac{1}{\lambda_{r,2}^2} \right) + \left(\frac{1}{\lambda_{r,4}^2} - \frac{1}{\lambda_{r,2}^2} \right) \right] \Bigg/ \left(\frac{\mathbf{E_S}}{\boldsymbol{\sigma}^2} \right) \quad (8)$$

$$\beta_3 = \left[\left(\frac{1}{\lambda_{r,1}^2} - \frac{1}{\lambda_{r,3}^2} \right) + \left(\frac{1}{\lambda_{r,2}^2} - \frac{1}{\lambda_{r,3}^2} \right) + \left(\frac{1}{\lambda_{r,4}^2} - \frac{1}{\lambda_{r,3}^2} \right) \right] \Bigg/ \left(\frac{\mathbf{E_S}}{\boldsymbol{\sigma}^2} \right) \quad (9)$$

$$\beta_4 = \left[\left(\frac{1}{\lambda_{r,1}^2} - \frac{1}{\lambda_{r,4}^2} \right) + \left(\frac{1}{\lambda_{r,2}^2} - \frac{1}{\lambda_{r,4}^2} \right) + \left(\frac{1}{\lambda_{r,3}^2} - \frac{1}{\lambda_{r,4}^2} \right) \right] \Bigg/ \left(\frac{\mathbf{E_S}}{\boldsymbol{\sigma}^2} \right) \quad (10)$$

the precoder may be written as:

$$\mathbf{L} = \frac{1}{\sqrt{4}} [\ \mathbf{w}_1 \quad \mathbf{w}_2 \quad \mathbf{w}_3 \quad \mathbf{w}_4\ ] \begin{bmatrix} \sqrt{1+\beta_1} & 0 & 0 & 0 \\ 0 & \sqrt{1+\beta_2} & 0 & 0 \\ 0 & 0 & \sqrt{1+\beta_3} & 0 \\ 0 & 0 & 0 & \sqrt{1+\beta_4} \end{bmatrix} \quad (11)$$

2) When the antenna correlation is zero, the eigenvalues of the matrix $\mathbf{R}_T^{1/2}$ are equal and therefore $\beta_i = 0, i = 1,2,3,4$ and the matrix of the eigenvectors equals the identity matrix. In this case the precoder is equivalent to the Tarokh orthogonal space-time coding.

3) When the antenna correlation is one, only one eigenvalue of matrix $\mathbf{R}_T^{1/2}$ is non zero. In this case the precoder is equivalent to a beamformer.

<u>The decoder in a four antenna transmission system</u>

The receiver is similar to the one used for the Tarokh space-time block coding scheme except it takes into account the linear transformation matrix **L**.

Four-antenna transmission system implementation in UMTS

A UMTS transmitter 402 and receiver 404 are shown in Figure 4. The UMTS frequency division duplex (FDD) downlink transmission-reception scheme includes antenna correlation dependent linear precoding as explained above. The transmitter 402 has some knowledge about the channel, namely the antenna correlation matrix **R**. In a UMTS network operating FDD downlink (e.g., from base station to mobile station), the antenna correlation information is obtained as feedback channel estimates 406 provided as bits sent by receiver 404 (e.g., the mobile station). The relevant modules are, at the transmitter, a linear precoder (**L**) 408, a processor (COR,410) which determines the antenna correlation matrix (**R**), and an R to L converter 412. The relevant modules at the receiver are a processor (COR,414) which determines the antenna correlation matrix (**R**), an R to L converter 416, and a space-time decoder 418.

At the transmitter 2, the linear precoder (**L**) 408 may be applied to the space-time encoded symbols provided from a space-time block encoder 420 after channel coding, rate matching interleaving, and modulation (shown as functional clock 422) in known fashion. The linear precoder L coefficients are computed based on the antenna correlation matrix **R** in the R to L converter 412. The computation of **R** (in a functional block denoted COR,410) may be based on channel estimates 406 fed back from the receiver 404. It may be performed by averaging over time-sequential channel estimates (running average) using a forgetting factor. The forgetting factor aims to weight the contribution of each new channel estimate as compared to the past channel estimates. It will thus be seen that fast fading may not be tracked but only slowly varying antenna correlations. This information may be fed back to the

transmitter using a low-rate feedback link, as available in UMTS. In a UMTS uplink channel there may be a number of bits available for communicating information to the transmitter about the received signal. The outputs of the linear precoder 408 are spread/scrambled 409 and subject to addition of Common Pilot Channel (CPICH) coding 411 bits before transmission.

At the receiver 404, received signals may be used to provide channel estimates in a channel estimation block 426 so as to be used to compute the antenna correlation matrix R in processor 414 (as at the transmitter). The signals may be also despread 428 and applied to a space-time block decoder 424. At the receiver 404 the space-time block decoder (STD,424) has essentially the same structure as a conventional one, but needs to consider instead of the channel estimates, the equivalent channel, defined as the linear transformation of the channel according to the coefficients of L, that is $\mathbf{H}_{eq} = \begin{bmatrix} h_{eq,1} & h_{eq,2} & h_{eq,3} & h_{eq,4} \end{bmatrix} = \mathbf{HL}$. As shown in Figure 2, the linear precoder **L** coefficients are estimated at the receiver from the processor (COR,414) which determines the antenna correlation matrix (**R**) and the R to L converter 416 present at the receiver 414. The outputs of the space-time decoder 424 may be provided to a combiner 430 and then channel decoded, inverse rate matched, deinterleaved and demodulated in known fashion (shown in Figure 4 as functional block 432).

Alternative Four -antenna Transmission System Implementation in UMTS

An alternative implementation is now described, in which instead of the linear transformation matrix **L** being determined at the transmitter from channel estimates provided by the receiver, the coefficients of linear transformation matrix L are provided by the receiver.

In this alternative embodiment, which is shown in Figure 5, the transmitter 502 may be given the coefficients of the precoder **L** by the receiver

504. In this UMTS transmitter 502 and receiver 504 operating with frequency division duplex (FDD) downlink, these coefficients are feedback bits sent by the mobile station. The proposed UMTS network is depicted in Figure 5, where the UMTS FDD downlink transmission-reception scheme includes antenna correlation dependent linear precoding as explained previously. The relevant module at the transmitter is a linear precoder (**L**) 508. The relevant modules at the receiver are a processor (COR,514) which determines the antenna correlation matrix (**R**), an R to L converter 516, and a space-time decoder 524.

At the transmitter, the linear precoder (**L**) may be applied to the space-time encoded symbols provided from the space-time block encoder 520 after channel coding, rate matching, interleaving, and modulation (shown as functional block 522) in known fashion. The outputs from the linear precoder 508 may be spread/scrambled 509 and subject to the addition of Common Pilot Channel (CPICH) 511 bits before transmission. The linear precoder **L** coefficients may be provided by the receiver 504 as explained below and fed back over air to the transmitter.

At the receiver, the computation of **R** (in a functional block denoted COR 514) is based on channel estimates provided from the channel estimator block 526. It may be performed by averaging over time sequential channel estimates (running average) using a forgetting factor. The forgetting factor aims to weight the contribution of each new channel estimate as compared to the past channel estimates; the aim being to take account of slowly-varying antenna correlations but not fast fading. The linear precoder (**L**) coefficients are computed based on the antenna correlation matrix **R** in the R to L converter 516.

At the receiver 504, received signals may be both used to provide channel estimates in a channel estimation block 526, and may be also despread 528 and applied to a space-time decoder 524. At the receiver, the

space-time block decoder (STD) 524 has identical structure to the conventional one, but needs to consider instead of the channel estimates, the equivalent channel, defined as the linear transformation of the channel according to the coefficients of L, that may be $\mathbf{H}_{eq} = \left[h_{eq,1} \quad h_{eq,2} \quad h_{eq,3} \quad h_{eq,4}\right] = \mathbf{HL}$. The outputs of the space-time decoder may be provided to a combiner 530 and then channel decoded, inverse rate matched, deinterleaved and demodulated in known fashion (shown in Figure 5 as functional block 532).

General

The two transmit antenna case and four transmit antenna case are examples. The approach extends to the cases in which there are three, or five or more transmit antennas.

While the particular invention has been described with reference to illustrative embodiments, this description is not meant to be construed in a limiting sense. It is understood that although the present invention has been described, various modifications of the illustrative embodiments, as well as additional embodiments of the invention, will be apparent to one of ordinary skill in the art upon reference to this description without departing from the spirit of the invention, as recited in the claims appended hereto. Consequently, the method, system and portions thereof and of the described method and system may be implemented in different locations, such as network elements, the wireless unit, the base station, a base station controller, a mobile switching center and/or a radar system. Moreover, processing circuitry required to implement and use the described system may be implemented in application specific integrated circuits, software-driven processing circuitry, firmware, programmable logic devices, hardware, discrete components or arrangements of the above components as would be understood by one of ordinary skill in the art with the benefit of

this disclosure. Those skilled in the art will readily recognize that these and various other modifications, arrangements and methods can be made to the present invention without strictly following the exemplary applications illustrated and described herein and without departing from the spirit and scope of the present invention It is therefore contemplated that the appended claims will cover any such modifications or embodiments as fall within the true scope of the invention.